Total Cost of Ownership (TCO) Analysis of Hydrogen Fuel Cells in Off Road Heavy-Duty Applications – Preliminary Results

DOE W.B.S. Number 9.3.0.6 Task No. 3

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Project ID: TA065

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Project Goals

- Evaluate the performance, durability and cost of fuel cells and H_2 storage in off-road vehicles and equipment for agriculture (FY22), construction (FY22), mining (FY 22), and MW-class mining trucks (FY23).
- Determine the total cost of ownership (TCO) considering the capital cost, fuel cost on application specific duty cycles, and operating and maintenance cost.
- Compare the TCO with the incumbent diesel engines and determine improvements needed for fuel cells and H_2 storage to be cost competitive.







Project Overview

Timeline

- Project start date: 10/01/2020
- Project end date: 9/30/2022

Budget

- FY21 DOE Funding: $250K
- FY22 DOE Funding: $300K
- FY23 DOE Funding: 0

HD Fuel Cells for Off-Road

Barriers Addressed

- B: System Cost
- C: Efficiency
- J: Thermal Management
- K: Life-Cycle Assessments

Partners/Interactions

- Argonne National Laboratory

Relevance/Potential Impact

- The nonroad sector accounts for 20% of the GHG emissions within the transportation sector.
- Construction, mining, and agriculture equipment are the largest contributors to nonroad GHG emissions and are responsible for more than half of all nonroad GHG emissions.
- Construction, mining, and agriculture used 10.2 billion gallons of diesel fuel in 2019 and were responsible for 113 Mt of GHG emissions (CO_2^e).
- High energy use and long duration of use makes decarbonizing with batteries particularly challenging in some of these applications

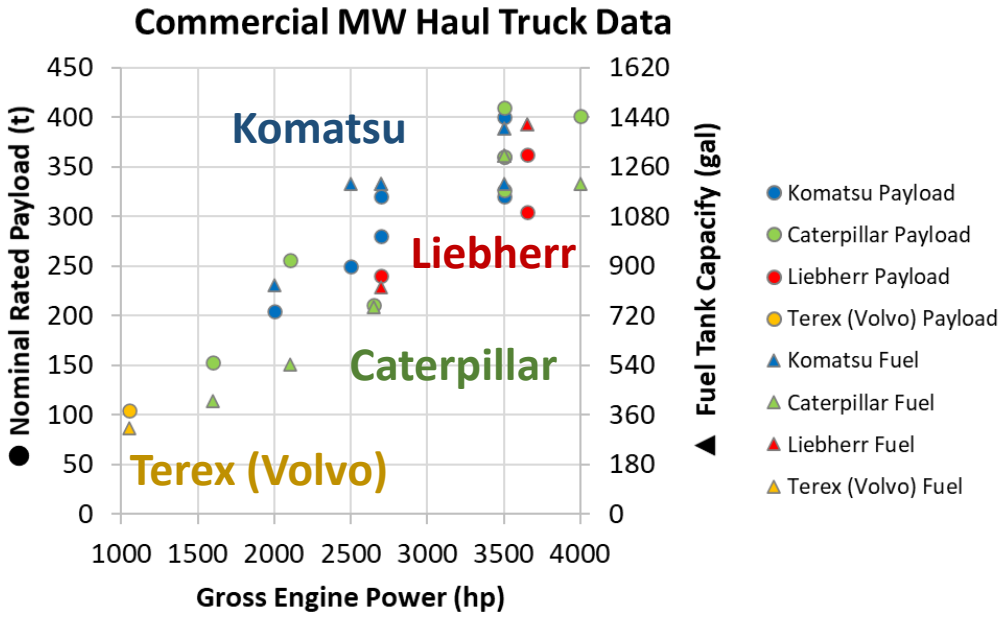
Approach

Motivation of Study on Megawatt-Sized Haul Trucks

- Mining industry accounts for ~7% of total global GHG emissions
- Diesel trucks consume 30% - 50% of a mine's total energy use
- Many OEMs offer trucks with 2000, 2700, and 3500 HP diesel engines

Scope of Study

- Initial study for diesel and fuel cell hybrid platforms equivalent to 3500 HP diesel engine
- Performance (component sizes, heat rejection, efficiency, fuel consumption) and durability of fuel cells (lifetime, performance degradation) and batteries (capacity fade) on truck duty cycle
- Total cost of ownership





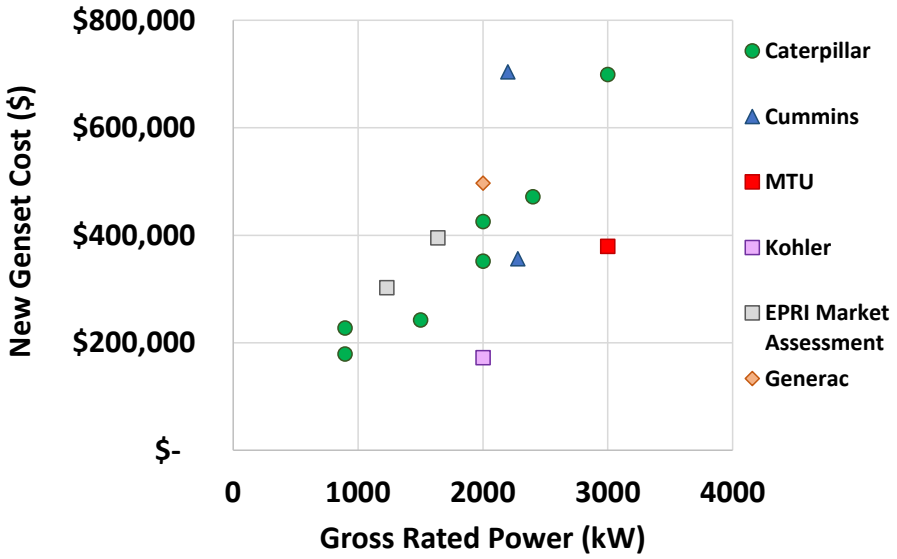




Performance and Cost Metrics

Approach

1. **Hybrid powertrain**: Fuel cell and battery sized to satisfy power demand at end of life (EOL)
2. **Thermal performance**: FCS platform has the same radiator frontal area and fan size as the diesel system
3. **Liquid hydrogen storage capacity**: Equal autonomy of diesel and fuel cell platforms



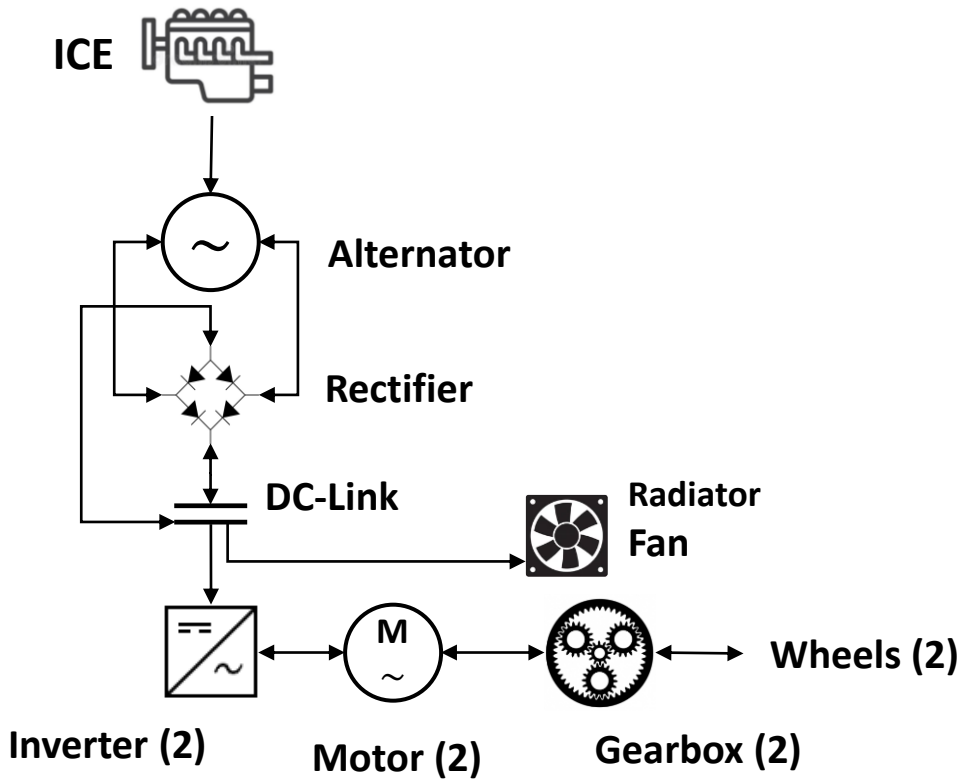
New Tier-2 Genset Cost: 209/kW$_e$

	Units	Genset	FCS Status	FCS Ultimate	Comments
Performance Metrics					
Engine Specific Power	W/kg	158	1000	1000	Genset includes diesel engine and alternator
Fuel Storage System Specific Energy	kWh/kg	8.4	6.0	6.0	OEM data for CAT C175-16, C175-20
ESS Specific Energy	Wh/kg		200	200	May need to ruggedize fuel cell system
BTMS Specific Power	W/kg		123	123	
Vehicle Parameters					
Annual Operating Hours	h	6,000	6,000	6,000	
Engine TBO (Diesel) or Lifetime (FCS)	h	20,000	25,000	25,000	TBO: Time between overhaul
Cost Metrics					
Tier-4 Genset or FCS	$/kW	250	323	60	20% allowance for Tier-4 modifications
Engine Overhaul, Stack Replacement	%	79	73	73	Percent of initial cost, reported as OPEX
Battery	$/kWh		157	80	DOE-EERE-VTO status and targets
Engine or FCS Routine Maintenance	$/MWh	5.3	8.3	8.3	Reported as O&M, Includes SCR catalyst replacement
Drivetrain Components					
Alternator	$/kW	59			Included in Genset
Rectifier	$/kW	90			
DC Link	$/kW	1.5			
DC-DC Converter	$/kW		75	75	Need 2 for 2-WD drivetrain
Inverter	$/kW	75	75	75	Need 2 for 2-WD drivetrain
AC Motor	$/kW	120	120	120	Need 2 for 2-WD drivetrain
Gearbox	$/kW	70	70	70	Need 2 for 2-WD drivetrain
Power Conditioning	$/kW	60	60	60	
Fuel Related Cost					
Fuel	$/gal, $/kg	3.25	5	3	
Lubrication	$/gal	0.49			Reported as O&M, 15% of fuel cost
Diesel Exhaust Fluid (Urea)	$/gal	0.18			SCR, Reported as O&M, 5.5% of fuel cost
Financial Parameters					
Economic Lifetime	years	15	15	15	
Salvage Value	% of list price	23	23	23	Zero salvage values for FCS and battery
Internal Rate of Return (IRR)	%	7	7	7	
Inflation	%	2	2	2	
Installation Cost Multiplier		1.3	1.3	1.3	30% installation surcharge

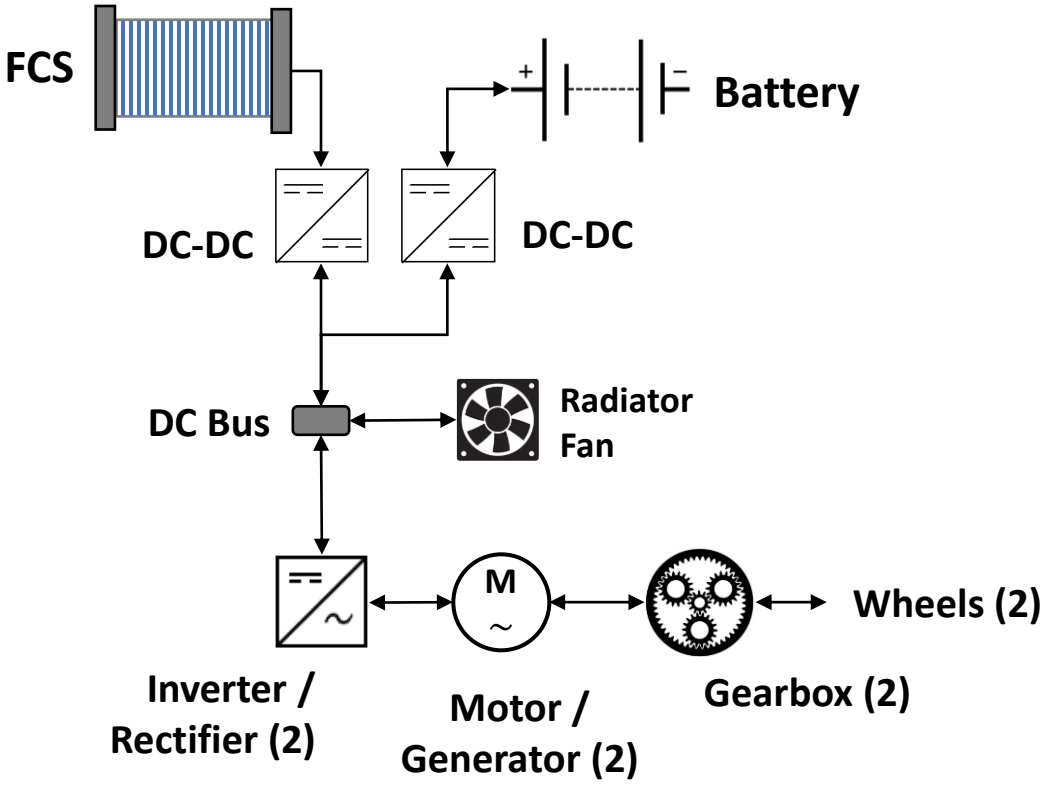
1. DC converter https://info.ornl.gov/sites/publications/files/Pub7166.pdf
2. Rectifier https://www.mdpi.com/1996-1073/11/12/3446
3. DC-link https://search.kemet.com/component-edge/#/distributor?pn=C4AQLBU4560A1WK
4. Inverter https://www.pnnl.gov/sites/default/files/media/file/Hydrogen_Methodology.pdf
5. Genset costs from USPE Global, PowerGen Enterprises, Generac Industrial Power, PowerSystemsToday, & EPRI

Accomplishments: System Configurations

Diesel Powertrain Configuration



Hybrid Fuel Cell Powertrain Configuration



Powertrain = Engine + Drivetrain

1. Komatsu 930E-5 Technical Paper AESS921-01, Komatsu America Corp (2019)
2. Caterpillar Performance Handbook 45th ed., Peoria, Illinois, U.S.A. (2015)
3. Feng et al., *J. Pow. Sources*, **454** (2020)
4. Terblanche et al., Technical and Economic Potential of Energy Recovery and Re-use on board Surface Mining Haul Trucks, (2018)
5. Koellner et al., *IEEE Trans.*, 51 **2** (2004)

Haul Route

Representative Haul Route from Mining Technology, 128 (2019)[2]

- Sectors 0 and 15 are ingress to and egress from the dump location, which must be traversed carefully as the dynamic soil poses significant danger to the haul truck [3,4]
- Ramp grade = 10% , fill takes 120 s [2,3,4,6]
- Truck nearly stationary during fill and dump
- Truck speeds = road limits except for the ascent [2,3,4,6]
- Actual ascent speed and time are calculated by a vehicle dynamics model [1,2,5]

1-D Dynamic Model for Calculating Power Demand[1, 2, 3]

- Force balance considering traction, braking and grade
- Rolling resistance and aerodynamic drag
- Model inputs: haul route, engine gross power, vehicle mass

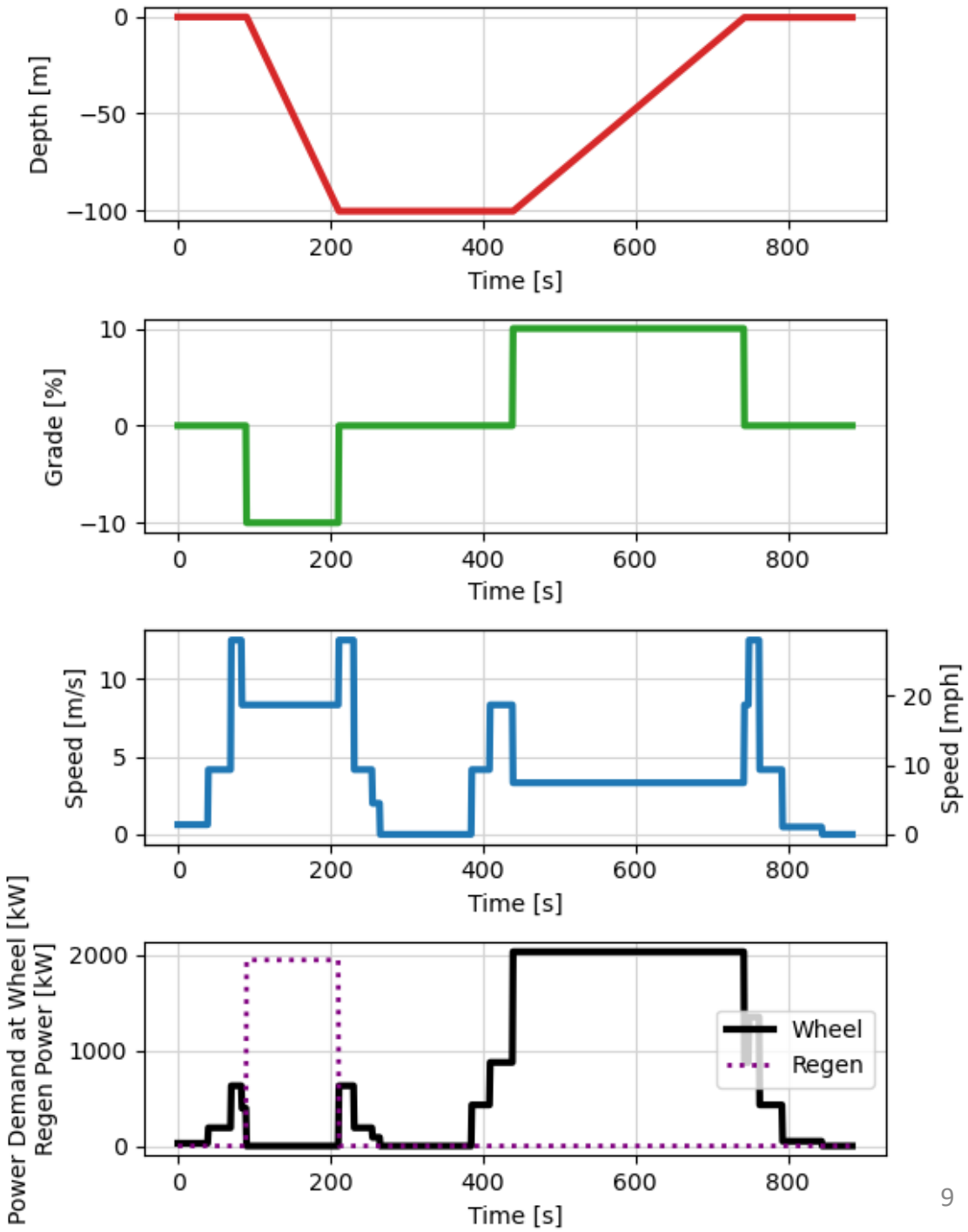
	Haul Route from Reference [2]					
	Sector	Driven Distance [m]	Grade %	Speed Limit [mph]	Normalized Truck Mass	Time [s]
Ingress	0	25	0	1.4	1	40
	1	125	0	9.3	1	30
	2	175	0	28	1	14
	3	50	0	18.6	1	6
Descent	**4**	**1005**	**-10**	**18.6**	**1**	**121**
	5	250	0	28	1	20
	6	100	0	9.3	1	24
	7	20	0	4.5	1	10
Fill	**8**	**1**	**0**	**0**	**2.28**	**120**
	9	100	0	9.3	2.28	24
	10	250	0	18.6	2.28	30
Ascent	**11**	**1005**	**10**	**18.6**	**2.28**	**calculated**
	12	50	0	18.6	2.28	6
	13	175	0	28	2.28	14
	14	125	0	9.3	2.28	30
Egress	15	25	0	1.1	2.28	52
Dump	**16**	**1**	**0**	**0**	**1**	**40**

1. Guzzella and Sciarretta, Vehicle Propulsion Systems, (2013)
2. Terblanche, Kearney, Nehring, and Knights, *Mining Technology*, **128** (2019)
3. Caterpillar Performance Handbook (2015)
4. US Dept. of Labor MSHA Haul Road Inspection Handbook (1999)
5. Zhang et al., *IEEE Trans*., 14 **9** (2018)
6. J. Mazumdar, "All electric operation of ultraclass mining haul trucks," 2013 IEEE Industry Applications Society Annual Meeting, 2013.

Power Demand

Duty Cycle Data Generated

- Inputs: 3500 hp engine, 258 t truck (empty), 330-t payload
- Outputs: power demand, vehicle speed
- Ascent speed and time are limited by engine rated power
  - ❖7.6 mph, 294 s for 2610 kW rated engine power
- Regenerative power and energy available (after battery charging + drivetrain losses) during descent on 10% grade: 1,851 kW_e and 62 kW_eh
- Traction power at wheel and cycle energy requirement: 2,033 kW and 202 kWh
- FC powertrain is lighter than diesel powertrain. Power demand duty cycles are mass-corrected.
- Duty cycle time is 883 s
  - ❖~40% idle, ~15% descent, ~35% ascent



Regenerating potential energy requires electric braking retarder & high-power ESS
Komatsu 950E-5: 2,700 hp gross engine power & 5,400 hp continuous retarding power

Hybrid Fuel Cell Powertrain and Heat Rejection

1. Maximum FCS Size for Hybrid Fuel Cell (FCH)

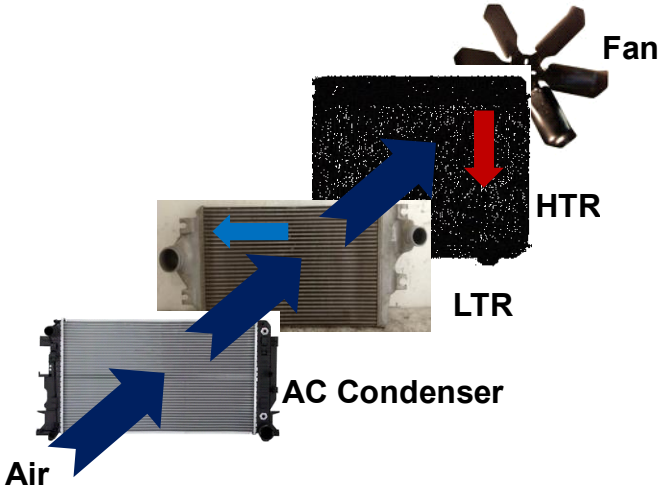
- Limit FCS size to reject waste heat using the same radiator frontal area and fan size as in a diesel mining truck
  - ❖ FCS max operating temperatures: 95°C stack, 50°C ambient
  - ❖ Diesel max operating temperatures: 110°C coolant exit, 50°C ambient
  - ❖ Cell voltage at rated power: 0.7 V at EOL

2. Battery Size and Charge/Discharge

- Charge-sustained mode: Zero net kWh, no external charging
- Charge battery during FCS idle and vehicle braking on descent
- Battery supplies supplemental power during ascent

3. Minimum FCS Size for Fuel Cell as Battery Charger (FCBC)

- Depending on state of charge (SOC), operate fuel cell at constant power except during vehicle braking



3500-hp Equivalent Mining Truck	Units	Diesel	FCH	FCBC
Powertrain				
Engine / FCS, w/o Fan	kW_e	2611	1387	1172
FC stack	kW_e		1568	1325
CEM Parasitic	kW_e		144	122
Other FCS Parasitics[1]	kW_e		38	32
Other System Parasitics[2]	kW_e	29	29	29
Radiator Fan	kW_e	209	209	209
BTMS[3]	kW_e		45	63
Battery Discharge Power	kW_e		1125	1350
Heat Duty Parameters				
High Temperature Radiator	kW	1352	1292	1092
CAC / Low Temperature Radiator	kW	451	130	110
AC Condenser	kW	7	7	7
BTMS[3]	kW		50	70

1. Other FCS parasitics include H_2 recirculation blower and coolant pump.
2. Other system parasitics include AC and hydraulic fan for direct air cooling of inverter, alternator and traction motor.
3. The diesel thermal management system includes a circuit for the rear-axle retarder. The FCS platform employs regenerative energy capture and rejects waste heat through the independent BTMS. Both systems share the same oil loop for cooling the final drive.

Engine Efficiency

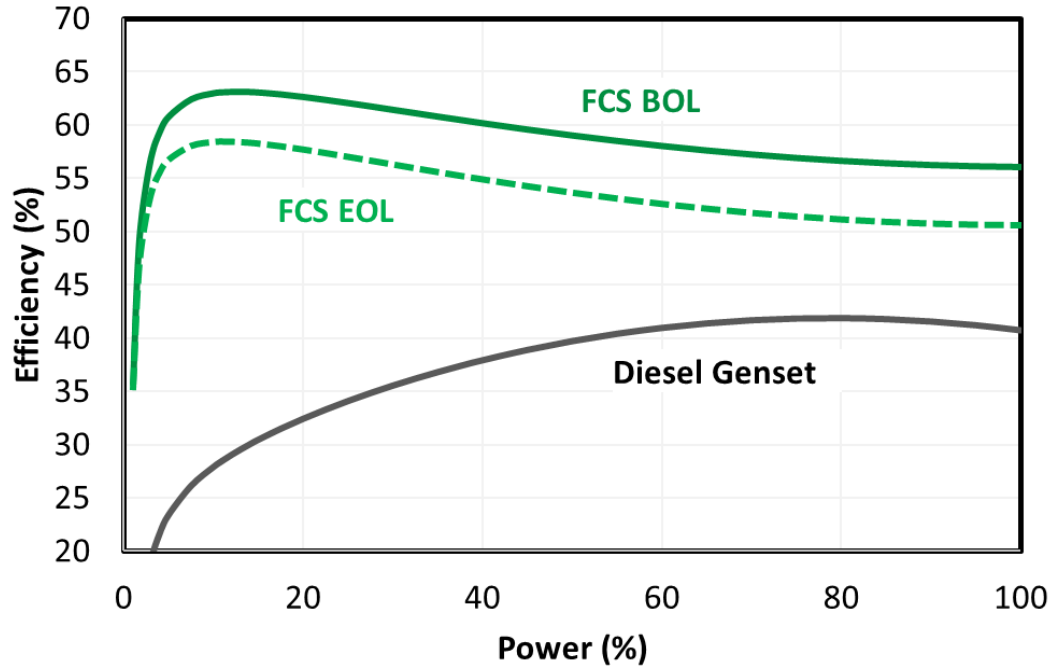
Fuel Cell Hybrid

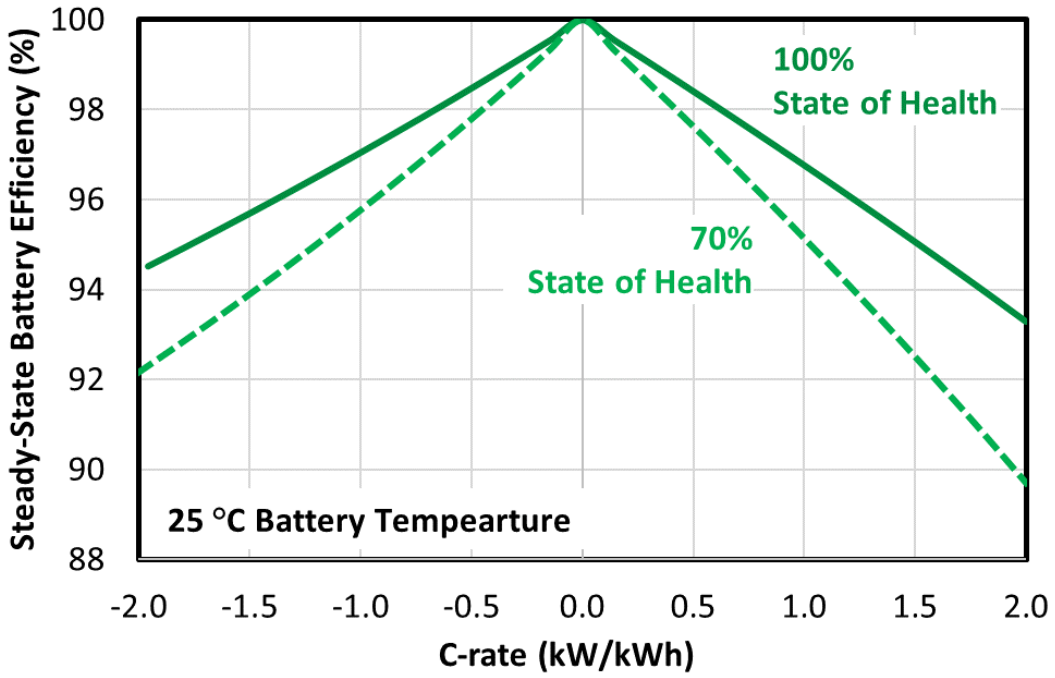
- FCS idles at 10% of rated power
- Peak FCS Efficiency: 63.1% at BOL
- FCS Efficiency at Rated Power: 56.0% at BOL and 50.6% at EOL
- Battery Efficiency: Lower during discharge and degrades more after capacity fade

Diesel

- 41% peak efficiency
- Steep drop in efficiency below 20% power

- All efficiencies without fan power
- Genset efficiency is modeled from CAT C175-16 genset data. The CAT C175-16 diesel genset powers several relevant vehicles: 793F (2650 hp), 794AC (3500 hp), 798AC (3500 hp)



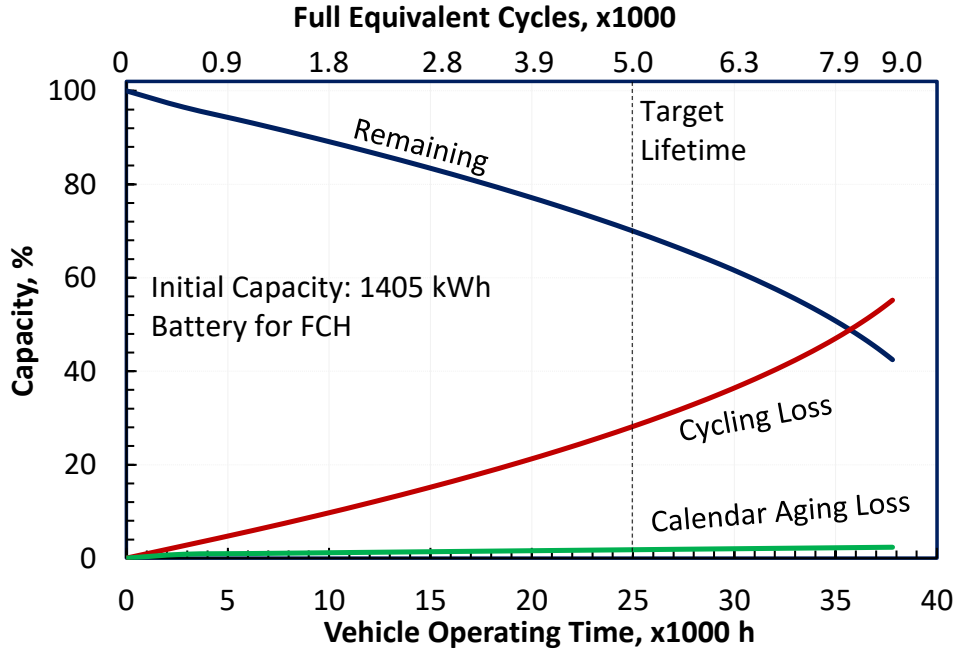


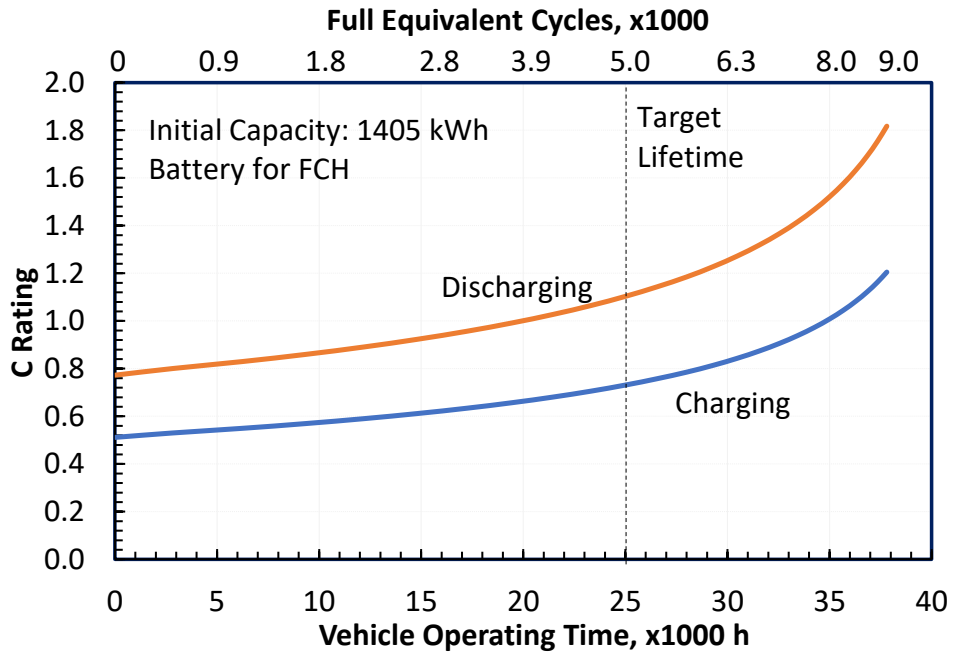
1. Caterpillar C175-16 Diesel Generator Set Product Data https://www.cat.com/en_US/products/new/power-systems/electric-power/diesel-generator-sets/1000028916.html

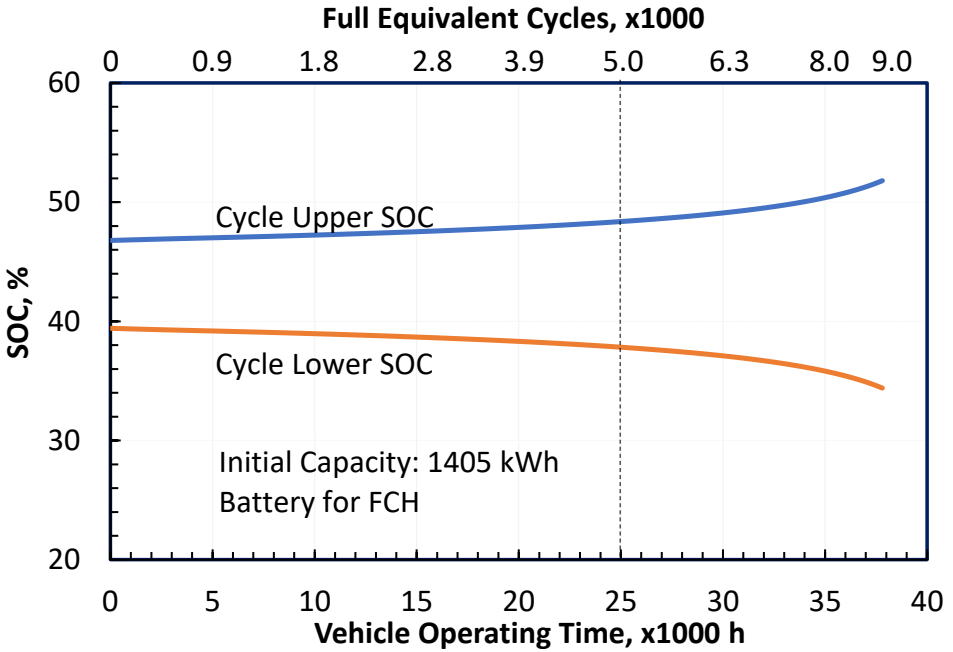
Energy Storage System (FCH)

Battery performance and lifetime based on literature data for lithium iron phosphate (LFP) chemistry

- Other battery chemistries such as LTO systems also candidates
- Battery sized for 30% capacity fade for same lifetime as FCS stack
- Battery Depth of Discharge: 7.5% at BOL increasing to 10.2% at EOL for FCH, 9.1% BOL and 13.1% EOL for FCBC
- Required battery capacity at BOL: 1405 kWh (FCH), 1468 kWh (FCBC)





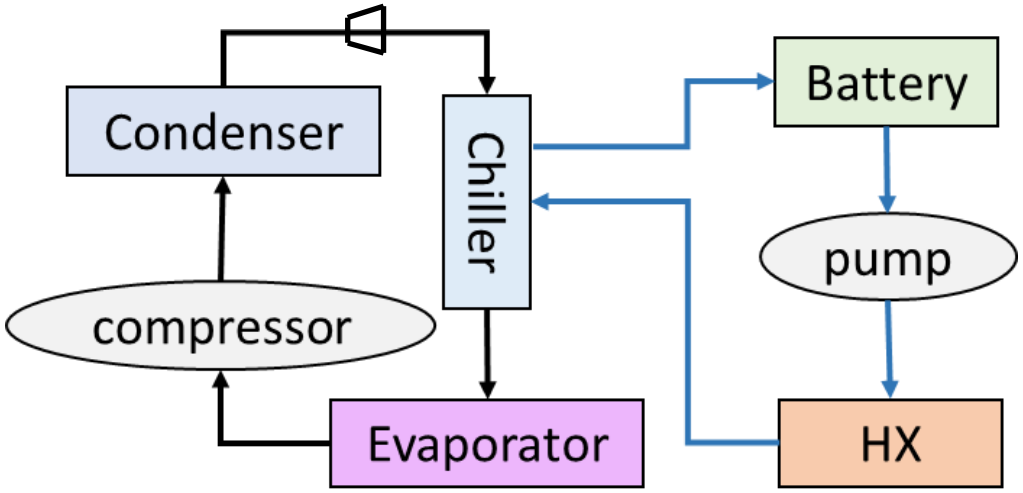


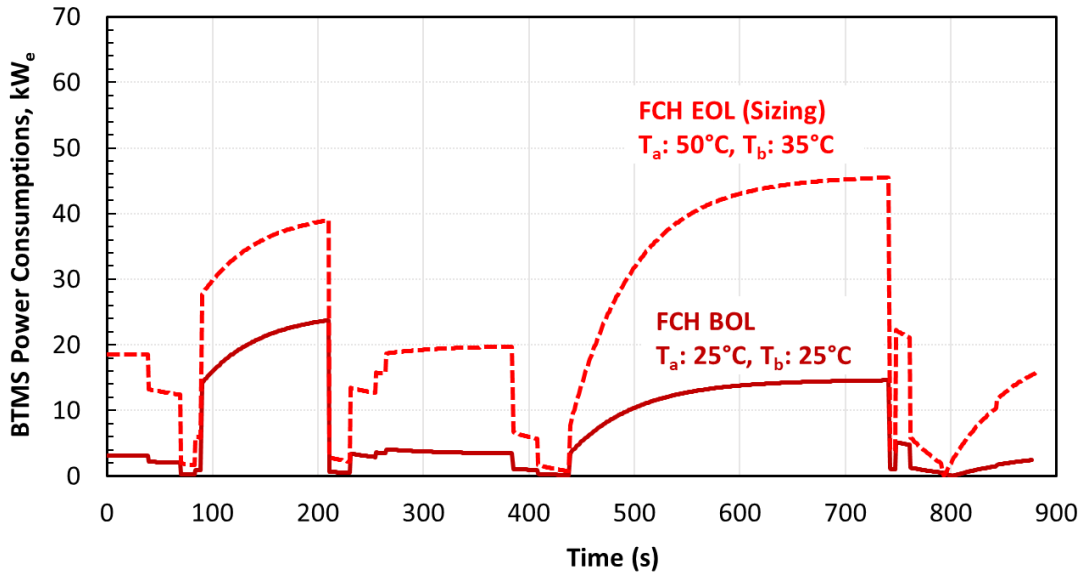
1. Modelling the cycling degradation of Li-ion batteries: Chemistry influenced stress factors (2021) https://www
2. The Degradation Behavior of LiFePO4/C Batteries during long-term calendar aging https://doi.org/10.3390/e
3. Sui et al., The Degradation Behavior of LiFePO4/C Batteries during Long-Term Calendar Aging. Energies 2021, 14, 1732
4. Olmos et al., Journal of Energy Storage 40 (2021) 102765

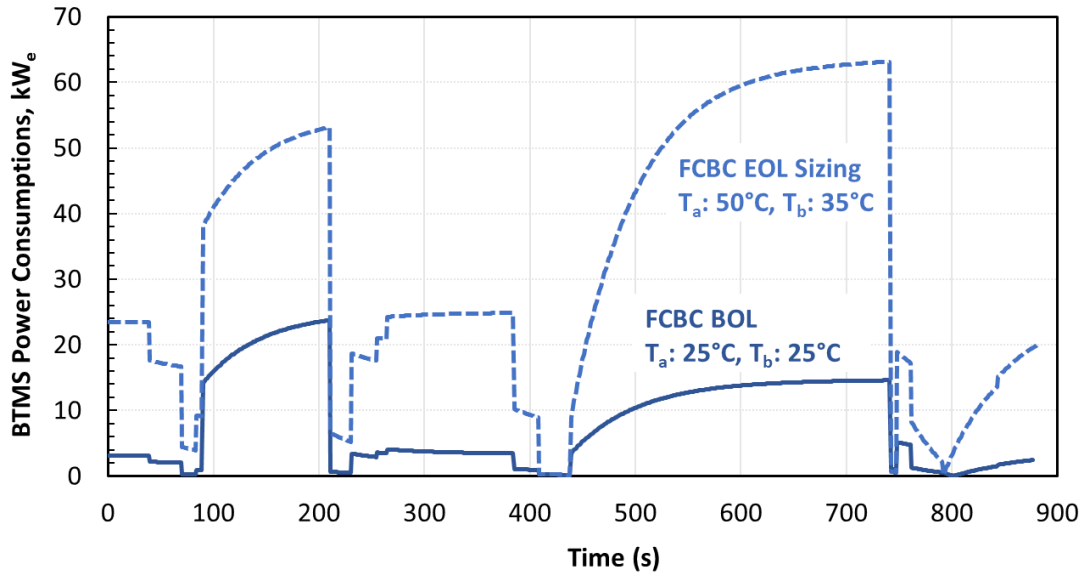
Battery Thermal Management System (BTMS)

AC cooling system sized for 35°C battery temperature, maximum discharge power at EOL and 50°C ambient temperature

- BTMS power consumption by compressor, condenser fan and pump: 45 kW_e FCH, 63 kW_e FCBC
- Battery temperatures and power consumption are lower at BOL especially at lower ambient temperature
- Only a fraction of available braking energy is recoverable at EOL and 50°C ambient temperature
- Nearly 100% of available braking energy may be recoverable at BOL and 25°C ambient temperature





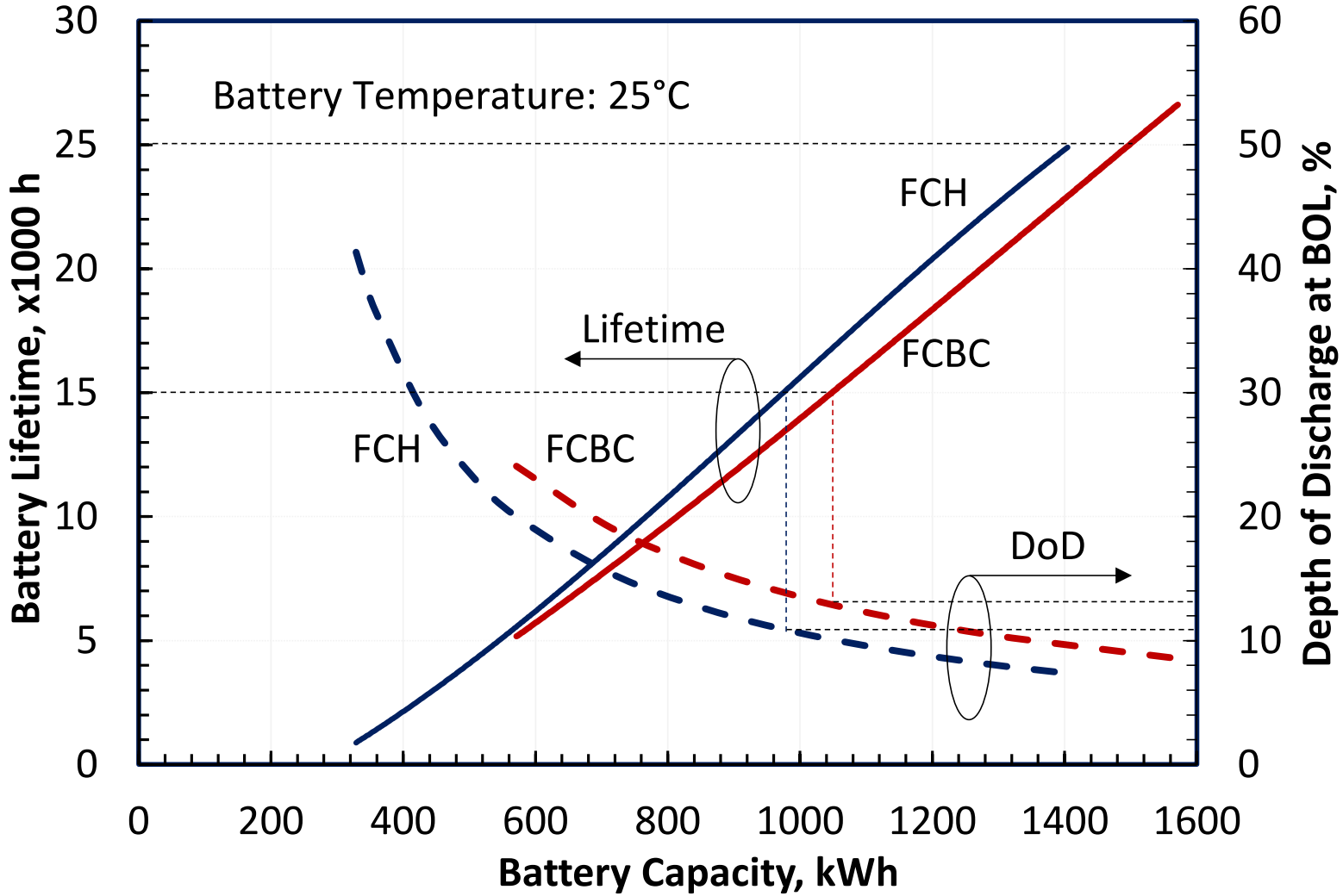


1. Hasselby, Dynamic Modelling of Battery Cooling Systems for Automotive Applications, Chalmers University of Technology (2013)

Trade-off between Battery Lifetime and Capacity

Trade-off option: Smaller battery operated at larger DOD to provide target charge and discharge power

- Advantages: Compact and lighter ESS, easier packaging
- Disadvantages: Shorter lifetime, downtime for battery replacement, lower efficiency, possibly higher lifetime cost



Power Profiles and Operating Strategies

Power outputs for all components calculated second-by-second over the duty cycle

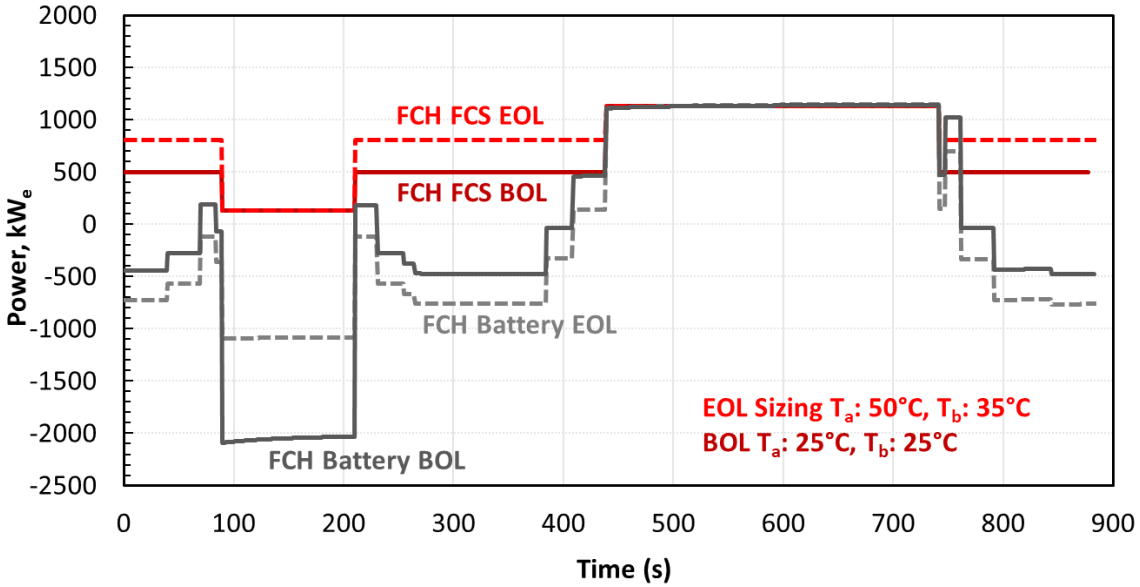
- Load-following FCS
- No FCS start-up/shut-down required on duty cycle
- Fuel storage sized for equal autonomy at EOL (19.1 h): 1311-gal diesel, 947-kg H_2 FCH, 1003-kg H_2 FCBC

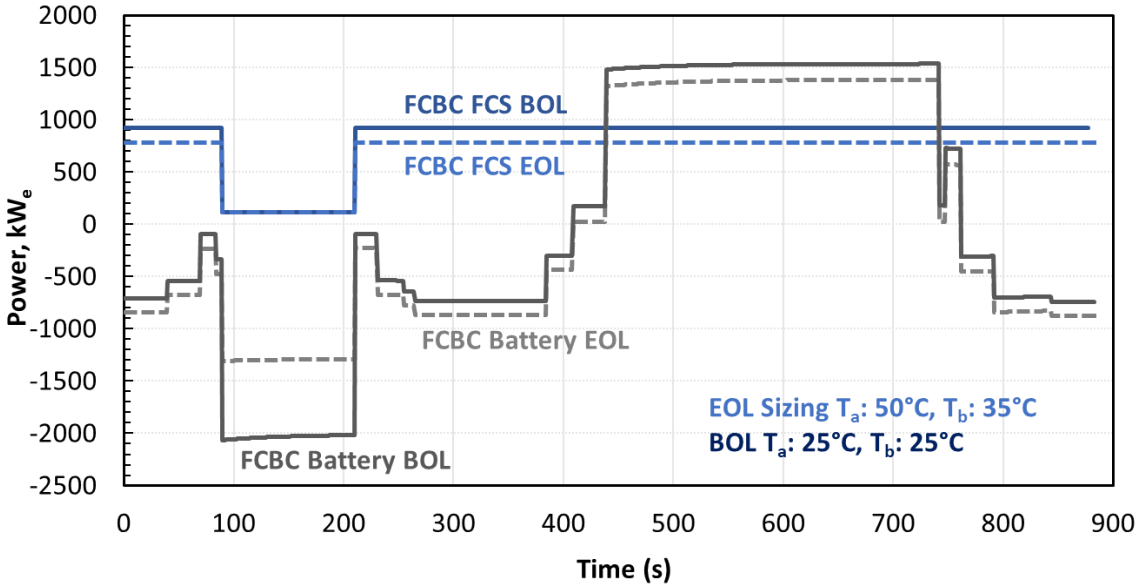
FCH: Hybrid Fuel Cell

- FCS delivers maximum power during ascent, idles during descent, and delivers 36% power otherwise
- Power split during ascent: 50% FCS, 50% battery
- Max battery power: 2,154 kW charge, 1125 kW discharge

FCBC: Fuel Cell as Battery Charger

- Fuel cell charges the battery and, depending on SOC and except during descent, can operate at constant power
- Power split during ascent: 40% FCS, 60% battery
- Max battery power: 2,134 kW charge, 1350 kW discharge





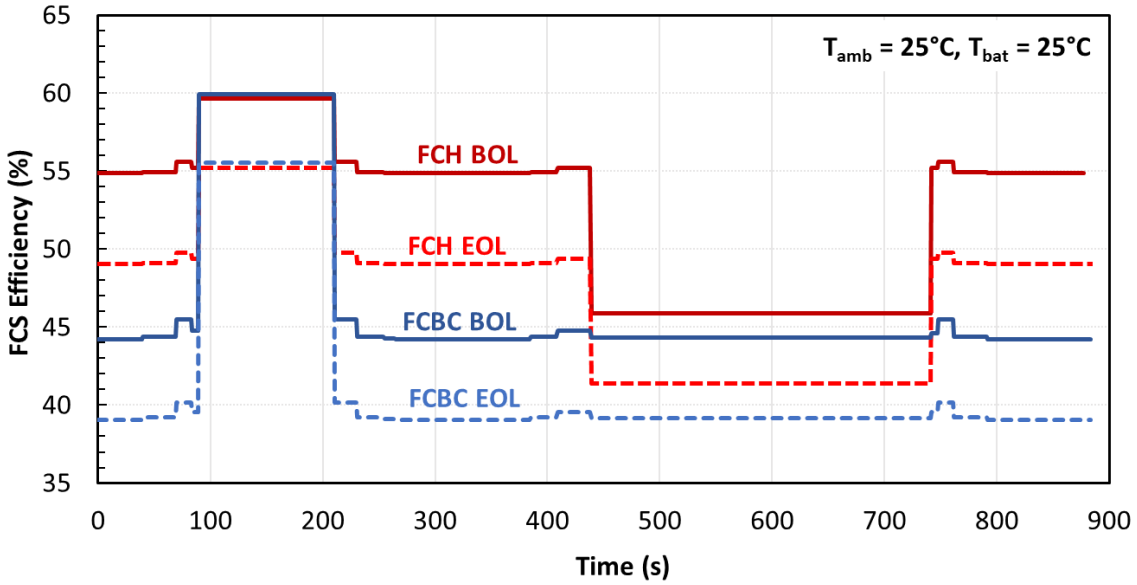
Powertrain Efficiencies and Fuel Consumption

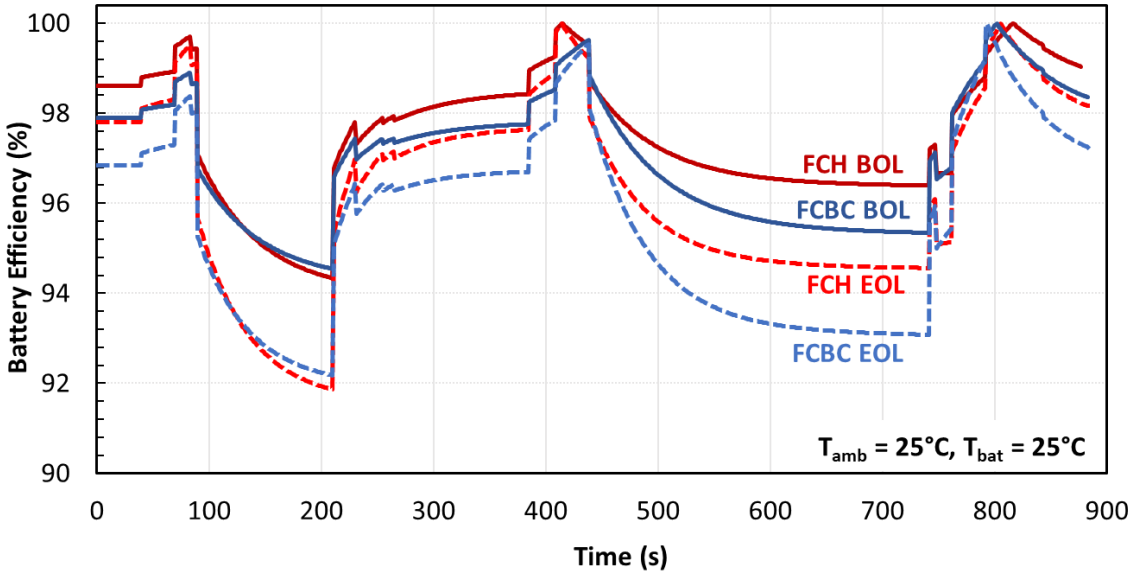
FCS platforms are more efficient than diesel

- FCH powertrain is 88% more efficient than the diesel powertrain at BOL and 81% more efficient over the lifetime
- On truck drive cycle, FCBC is less efficient than FCH because, except during descent, it operates closer to rated power (87-90% of rated power)
- Lower battery efficiency for FCBC platform because of higher C-rates during charge and discharge

	Diesel	FCH BOL	FCH EOL	FCBC BOL	FCBC EOL
Fuel Consumption	16.5 gal/cycle	9.9 kg/cycle	11.3 kg/cycle	11.3 kg/cycle	13.2 kg/cycle
Powertrain Efficiency	20.3%	38.3%	33.6%	33.7%	28.8%

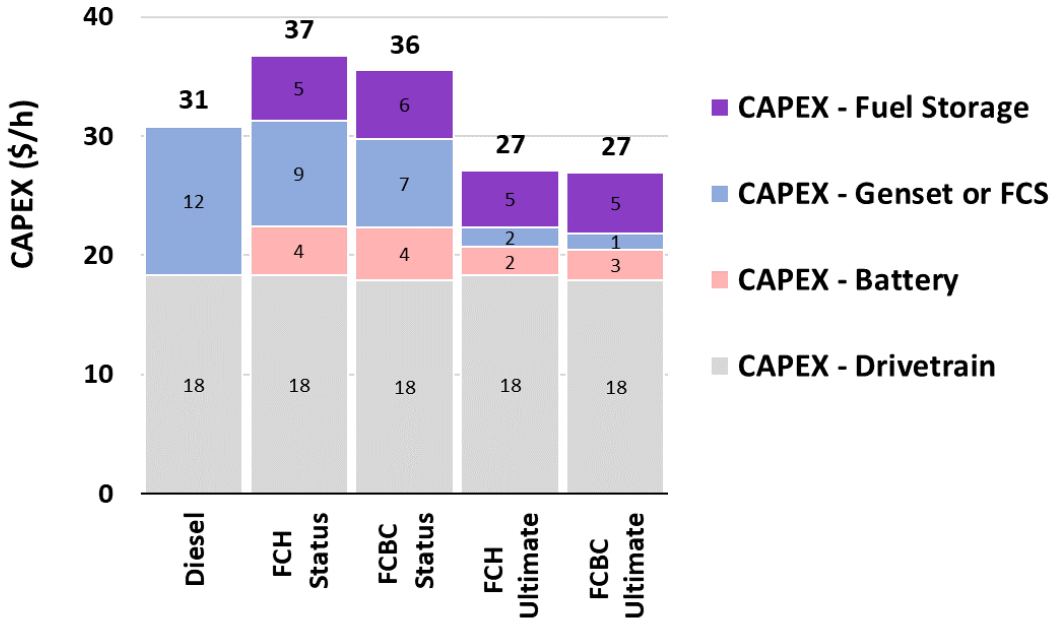
$$\langle \eta_{PT} \rangle = \frac{\int_0^\tau \mathrm{P}_{\mathrm{wheel}} dt}{\int_0^\tau \dot{m}_{\mathrm{H_2}} \mathrm{LHV}_{\mathrm{H_2}} dt}$$



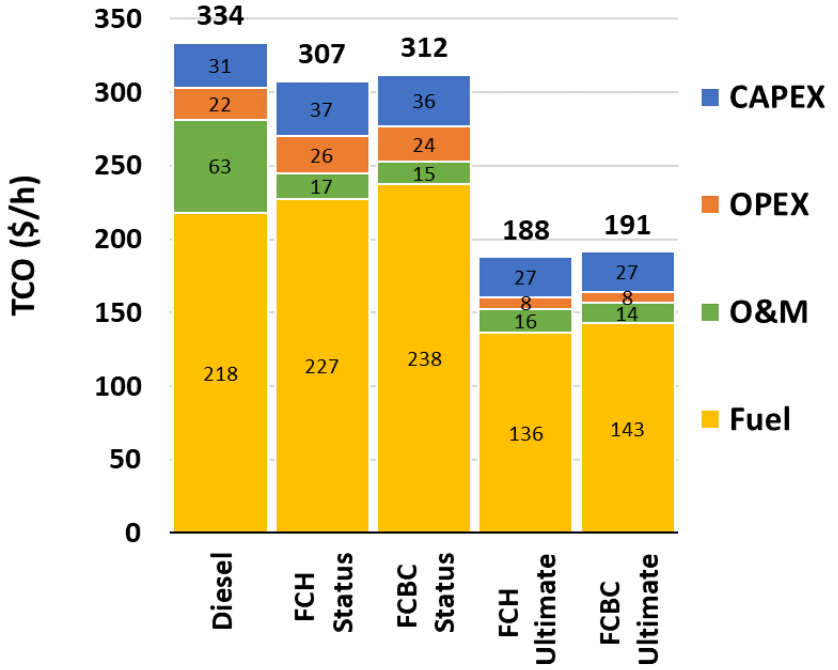


Total Cost of Ownership (TCO)

- Fuel cost dominates TCO, ~75% for FCS, ~65% for diesel
- FCH is the lowest TCO platform
  $27/h less than diesel (FCH status),
  $146/h less than diesel (FCH ultimate)
- FCBC has $9-4/h higher TCO than FCH but may be the preferred option as it mitigates the membrane durability issue
- Breakeven H_2 cost relative to diesel at $3.25/gal
  FCH Status: $5.58/kg-$H_2$
  FCBC Status: $5.38/kg-$H_2$
  FCH Ultimate: $6.19/kg-$H_2$
  FCBC Ultimate: $5.98/kg-$H_2$



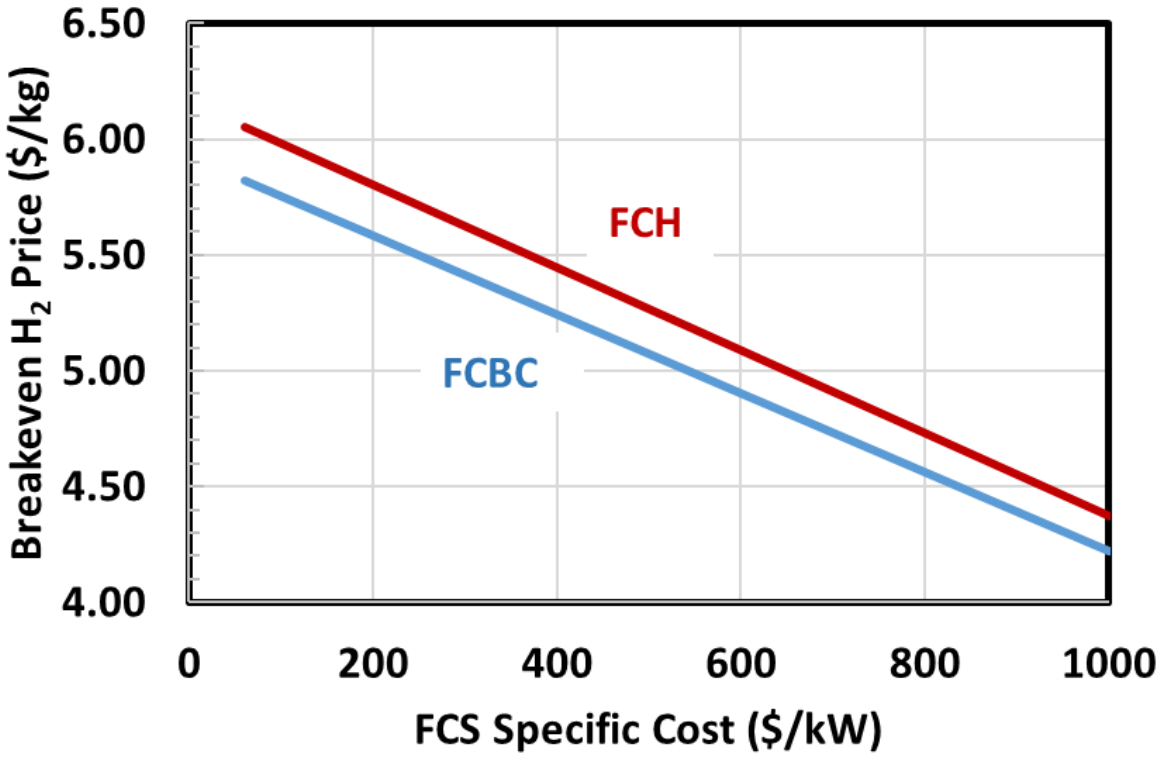
- CAPEX includes Tier-4 diesel or FC powertrain and fuel storage. All other common-cost elements, such as chassis and tires, are omitted.
- OPEX includes amortized costs of FC stack and battery replacement, and major diesel engine overhaul.
- O&M includes routine repair of FCS and Tier-4 diesel platforms, diesel lubrication, DEF, SCR catalyst recharge and insurance

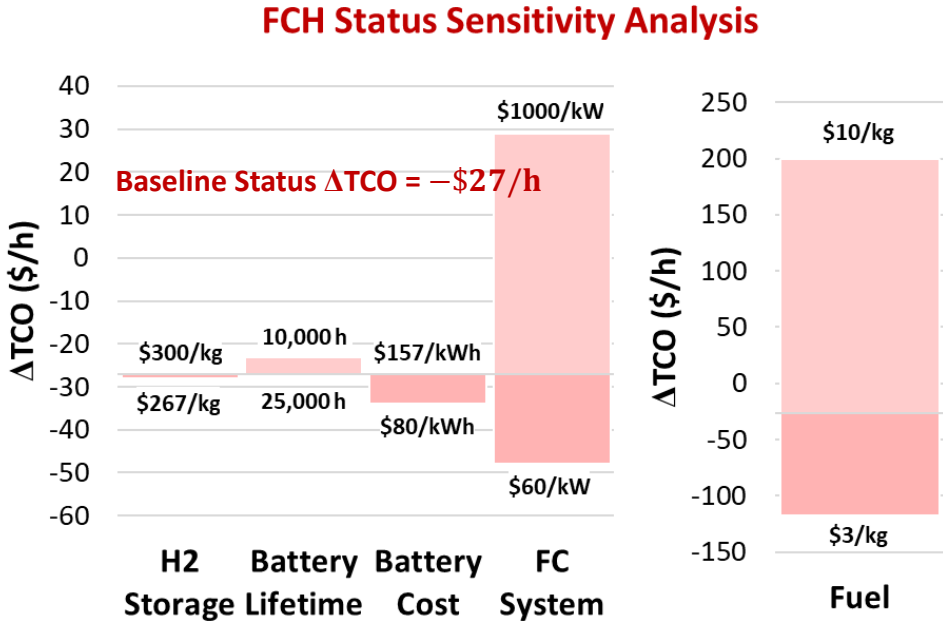


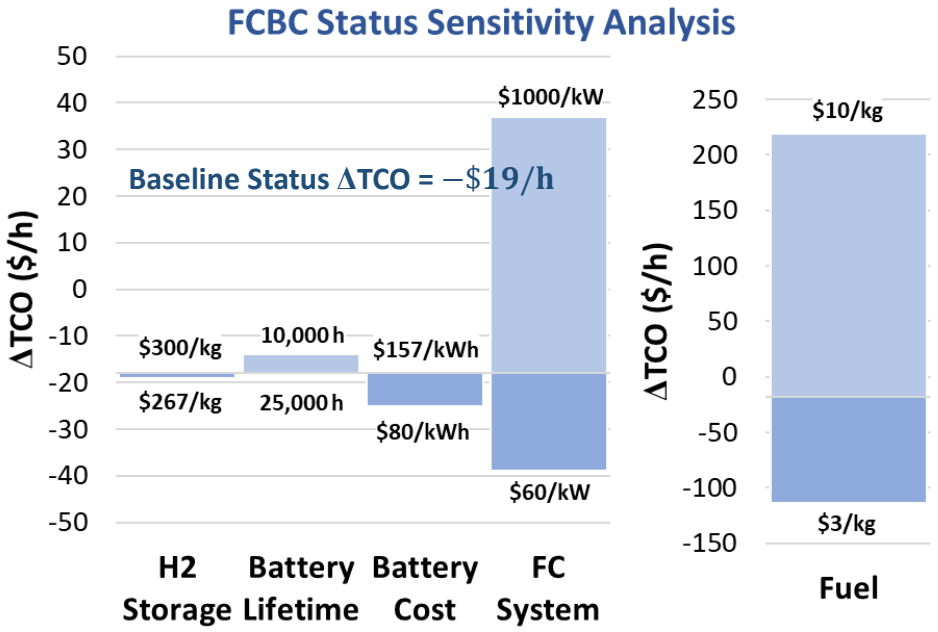
1. Case Construction https://tco.casece.com/northamerica/en-us
2. VTO FCS and BAT targets
3. https://info.ornl.gov/sites/publications/files/Pub7166.pdf
4. https://www.mdpi.com/1996-1073/11/12/3446
5. https://search.kemet.com/component-edge/#/distributor?pn=C4AQLBU4560A1WK
6. https://www.pnnl.gov/sites/default/files/media/file/Hydrogen_Methodology.pdf

Sensitivity Analysis

- TCO is most sensitive to FCS and fuel cost
- Breakeven H_2 cost as function of FCS cost relative to diesel at $3.25/gal







Collaboration and Coordination

Industrial Companies Contacted for Feedback

- AGCO Power
- Caterpillar
- CNH Industrial
- Dawnbreaker
- Empire Tractor
- First Mode
- Fortescue Future Industries
- John Deere
- Komatsu
- Volvo Trucks North America

Presentations at the Mission Innovation Workshop and Working Group Meetings

1. Rajesh K Ahluwalia and Xiaohua Wang, Thermal Management for Heavy-Duty Fuel Cell Product Applications, MI Clean Hydrogen HD Off Road Fuel Cell / Powertrain Task Team, 18 October 2022.
2. Rajesh K. Ahluwalia, Xiaohua Wang, Dionissios Papadias, and Andrew G. Star, Total Cost of Ownership (TCO) of Hydrogen Fuel Cells in Megawatt-Sized Haul Trucks for Mining Applications, MI Clean Hydrogen Off-Road Hydrogen-Powered Fuel Cells and Equipment, Working Group Virtual Meeting, August 19, 2022.
3. R. K. Ahluwalia, X. Wang, A. Star, and D. D. Papadias, Total Cost of Ownership (TCO) Analysis of Hydrogen Fuel Cells in Off Road Heavy-Duty Applications – Preliminary Results, Mission Innovation Hydrogen Fuel Cell Off-Road Equipment and Vehicles Virtual Workshop, September 22-24, 2021.

Summary

Relevance:	Construction, mining, and agriculture equipment are the largest contributors to nonroad GHG emissions. High energy use and autonomy makes are particularly challenging for batteries in some applications.
Approach:	For economy of scale, use fuel cell systems (FCS) being developed for heavy-duty trucks. Size fan and radiator frontal area for FCS heat load and operating temperature. Adapt LH_2 storage systems being developed for heavy-duty trucks and select fuel storage capacity for equal autonomy (time between refueling) at end of life (EOL). Use hybrid platforms with batteries to extend PEFC stack lifetime by voltage clipping and improve fuel economy by capturing regenerative energy.
Progress:	Demonstrated the feasibility of replacing a 3600-hp diesel engine in a MW-class mining truck with hybrid fuel cell and battery electric drivetrains: FCH: 1387 kW FCS + 984 kWh ESS; FCBC: 1172 kW FCS + 1028 kWh ESS; all ratings at EOL. Showed that the heat rejection challenge in mining trucks can be met by downsizing the fuel cell by 47% (FCH configuration) to reject the waste heat with the same size radiator and fans as in the diesel engine. Evaluated the concept of further downsizing the fuel cell to 55% (FCBC configuration) to mitigate membrane degradation by lowering operating temperatures. Proposed and evaluated the concept of oversizing the battery capacity and operating at optimum conditions (SOC band, thermal management) for same lifetime as the fuel cell. Evaluated the total cost of ownership (TCO) of FCH and FCBC configurations and determined the breakeven H_2 cost for TCO parity as \$5.38-6.19/kg-H_2 relative to diesel at \$3.25/gal.
Collaborations:	AGCO Power, Caterpillar, CNH, Dawnbreaker, Empire Tractor, First Mode, Fortescu, John Deere, Komatsu, Volvo Trucks
Remaining Work:	Continue to support Mission Innovation efforts and document results. 1. R. K Ahluwalia, X. Wang, D. D. Papadias and A. G. Star, Performance and Total Cost of Ownership of a Fuel Cell Hybrid Mining Truck, Energies 2023, 16(1), 286. 2. R. K Ahluwalia, X. Wang, A. G. Star, and D. D. Papadias, Performance and Cost of Fuel Cells for Off-road Heavy-duty Vehicles, Intl. J. Hydrogen Energy, 2022, 47, 20.

Technical Backup and Additional Slides

Proposed Future Work

1. The study on mine haul trucks was completed.

2. At DOE's discretion, new work may begin on refueling infrastructure for off road heavy-duty applications.

3. Continue to support Mission Innovation efforts as requested.

Technology Transfer Activities

Presentations at the Mission Innovation Workshop and Working Group Meetings

1. Rajesh K Ahluwalia and Xiaohua Wang, Thermal Management for Heavy-Duty Fuel Cell Product Applications, MI Clean Hydrogen HD Off Road Fuel Cell / Powertrain Task Team, 18 October 2022.
2. Rajesh K. Ahluwalia, Xiaohua Wang, Dionissios Papadias, and Andrew G. Star, Total Cost of Ownership (TCO) of Hydrogen Fuel Cells in Megawatt-Sized Haul Trucks for Mining Applications, MI Clean Hydrogen Off-Road Hydrogen-Powered Fuel Cells and Equipment, Working Group Virtual Meeting, August 19, 2022.
3. R. K. Ahluwalia, X. Wang, A. Star, and D. D. Papadias, Total Cost of Ownership (TCO) Analysis of Hydrogen Fuel Cells in Off Road Heavy-Duty Applications – Preliminary Results, Mission Innovation Hydrogen Fuel Cell Off-Road Equipment and Vehicles Virtual Workshop, September 22-24, 2021.

Response to Reviewers

This is a new project. It was not reviewed last year.

Publications and Presentations

1. R. K Ahluwalia, X. Wang, D. D. Papadias and A. G. Star, Performance and Total Cost of Ownership of a Fuel Cell Hybrid Mining Truck, Energies 2023, 16(1), 286.
2. R. K Ahluwalia, X. Wang, A. G. Star, and D. D. Papadias, Performance and Cost of Fuel Cells for Off-road Heavy-duty Vehicles, Intl. J. Hydrogen Energy, 2022, 47, 20.
3. Rajesh K Ahluwalia and Xiaohua Wang, Thermal Management for Heavy-Duty Fuel Cell Product Applications, MI Clean Hydrogen HD Off Road Fuel Cell / Powertrain Task Team, 18 October 2022.
4. Rajesh K. Ahluwalia, Xiaohua Wang, Dionissios Papadias, and Andrew G. Star, Total Cost of Ownership (TCO) of Hydrogen Fuel Cells in Megawatt-Sized Haul Trucks for Mining Applications, MI Clean Hydrogen Off-Road Hydrogen-Powered Fuel Cells and Equipment, Working Group Virtual Meeting, August 19, 2022.
5. R. K. Ahluwalia, X. Wang, A. Star, and D. D. Papadias, Total Cost of Ownership (TCO) Analysis of Hydrogen Fuel Cells in Off Road Heavy-Duty Applications – Preliminary Results, Mission Innovation Hydrogen Fuel Cell Off-Road Equipment and Vehicles Virtual Workshop, September 22-24, 2021.

Conclusions

Performance

1. **Heat Rejection**: downsize the fuel cell by 47% (FCH) to reject waste heat with the same size radiator and fans as in the diesel engine
2. **Membrane Lifetime**: downsize the fuel cell by 55% (FCBC) to mitigate membrane durability issue
3. **Electrode Lifetime**: oversize the stack, overload the catalyst and clip voltage to achieve target lifetime.
4. **Battery Lifetime**: oversize the capacity and operate at optimum conditions (SOC band, thermal management) for same lifetime as the fuel cell.

Cost

1. **Volume Manufacturing**: fuel cells can be competitive with diesel trucks if manufactured at volume (1000 units/y)
2. **Cost Benefits**: Lower fuel consumption and lower maintenance and operating cost which may also reduce unscheduled downtime.

Future Work

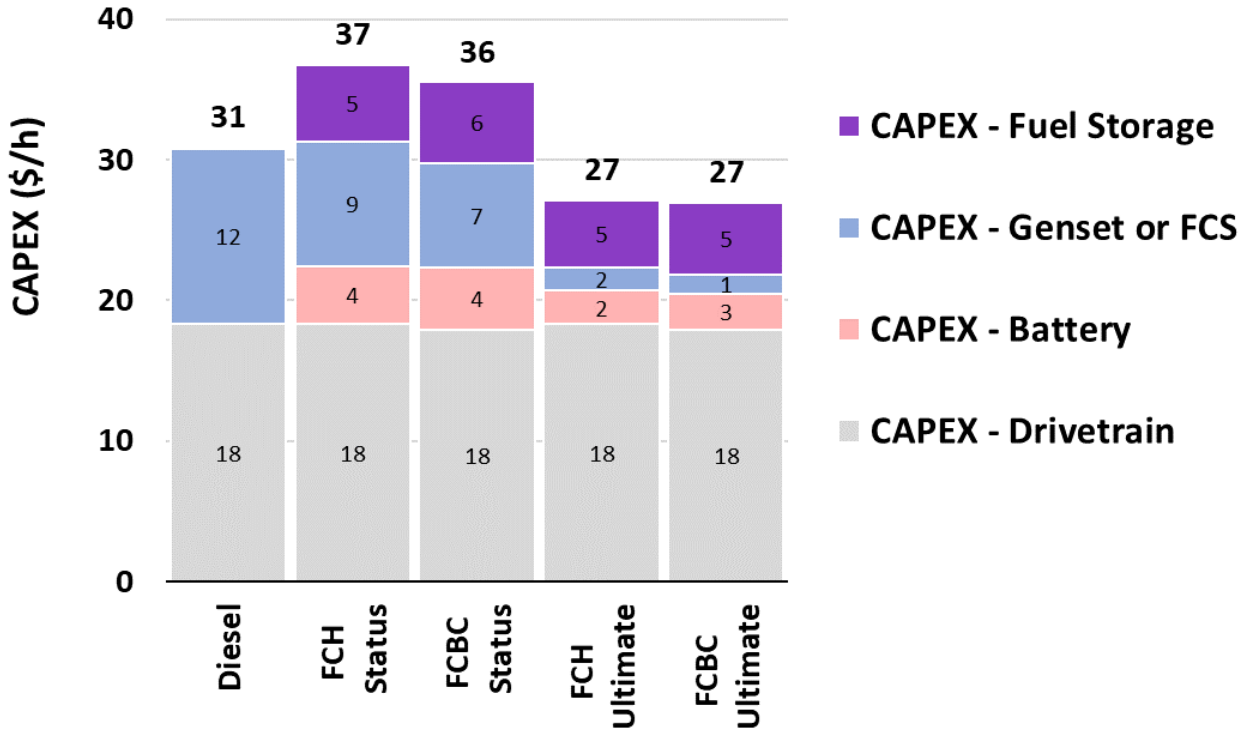
1. **Demonstrate fuel cell lifetime** on mining truck duty cycle
2. **Demonstrate battery lifetime** on mining truck duty cycle

	ΔTCO: FCS ($/h) - Diesel ($/h)			
	FCH Status	FCBC Status	FCH Ultimate	FCBC Ultimate
CAPEX	6	9	-3	-3
Fuel	9	20	-82	-75
OPEX	4	2	-14	-14
O&M	-46	-48	-47	-49
Total	-27	-18	-145	-142

Total Cost of Ownership: CAPEX

CAPEX Breakdown

- **Platform Ranking**: FCBC Status > FCH Status > Diesel > FCH Ultimate ~ FCBC Ultimate
- **Diesel**: Drivetrain > Genset
- **FCH Status**: Drivetrain > FCS > Fuel Storage > Battery
- **FCBC Status**: Drivetrain > FCS > Fuel Storage > Battery
- **FCH Ultimate**: Drivetrain > Fuel Storage > (FCS ~ Battery)
- **FCBC Ultimate**: Drivetrain > Fuel Storage > (FCS ~ Battery)



- CAPEX includes Tier-4 diesel or FC powertrain and fuel storage. All other common-cost elements, such as chassis and tires, are omitted.
- CAPEX only includes the cost of first-installed FCS and battery. The cost of FC stack and battery replacements are considered as OPEX.
- CAPEX has been amortized over the component economic lifetimes to obtain $/h.

Stack Temperature and Fan Power

Stack Temperature and Fan Power

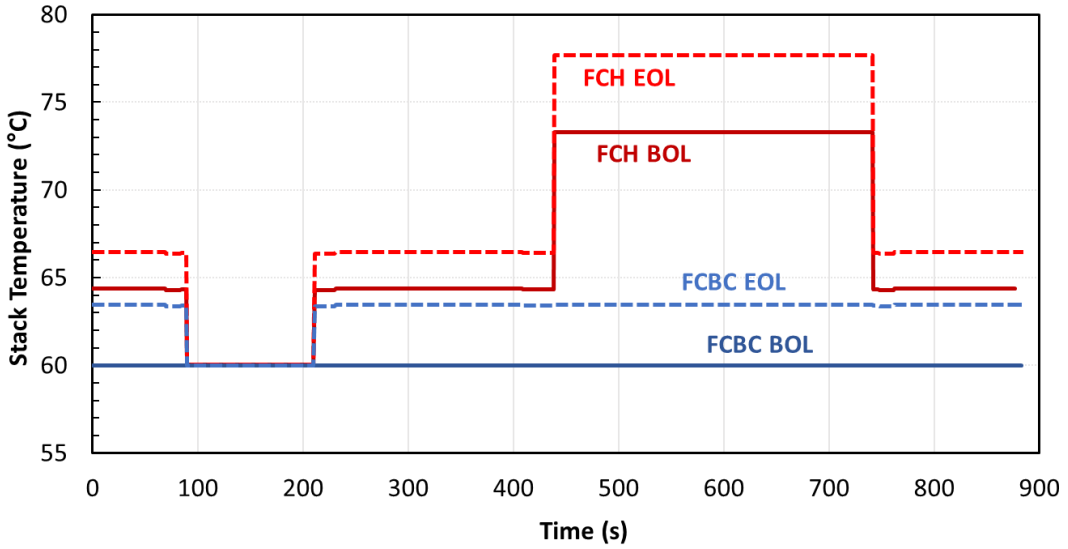
- Fan power and stack temperature are lower for lower truck power demands

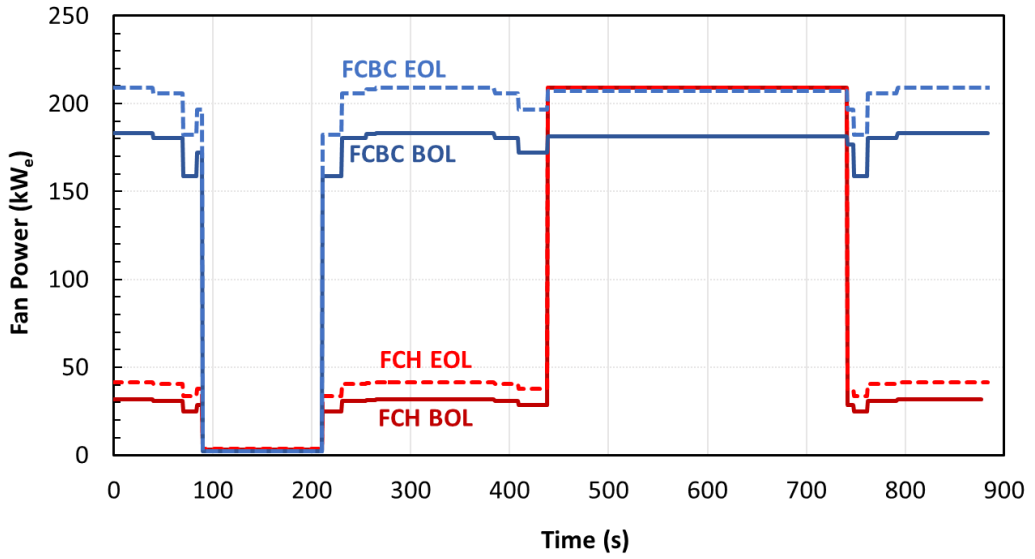
FCH

- During ascent, radiator fan draws 209 kW at EOL and 150 kW at BOL to maintain the stack temperature to 78°C at EOL and 74°C at BOL for 25°C ambient (95°C for 50°C ambient)

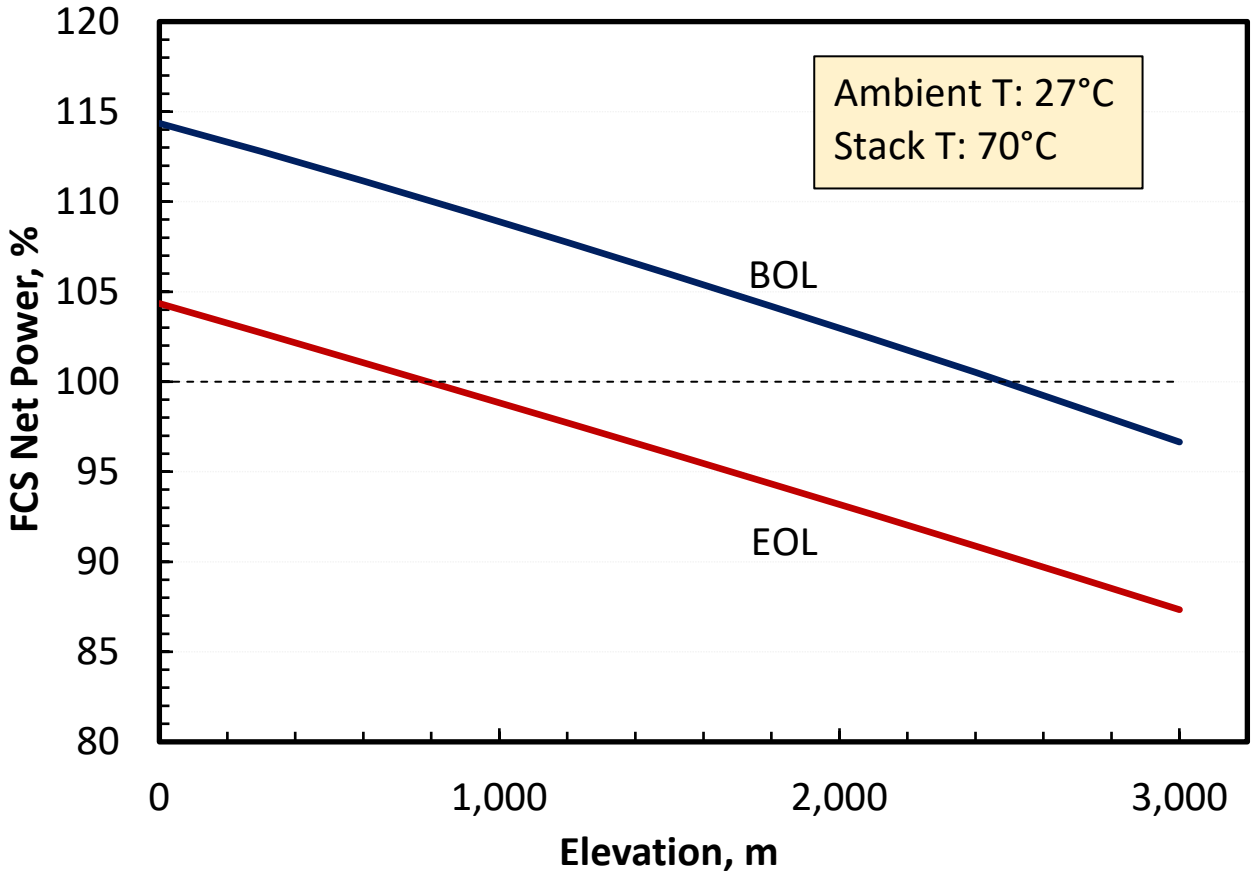
FCBC

- Radiator fan draws 209 kW and 181 kW to maintain the stack temperature at 64°C at EOL and 60°C at BOL for 25°C ambient over full lifetime (78°C at ascent for 50°C ambient)
- Better membrane durability than FCH





FCS Performance at High Elevation



ADDITIONAL CONSIDERATIONS

Mine Depth?
E.g., Minera Escondida (world's largest copper mine) = 3,050 meters
450 meters depth at bottom in 2004, 750 "ultimate/final" meters depth
https://www.bhp.com/-/media/bhp/documents/investors/reports/2004/escondidasitevisit240404.pdf?la=en

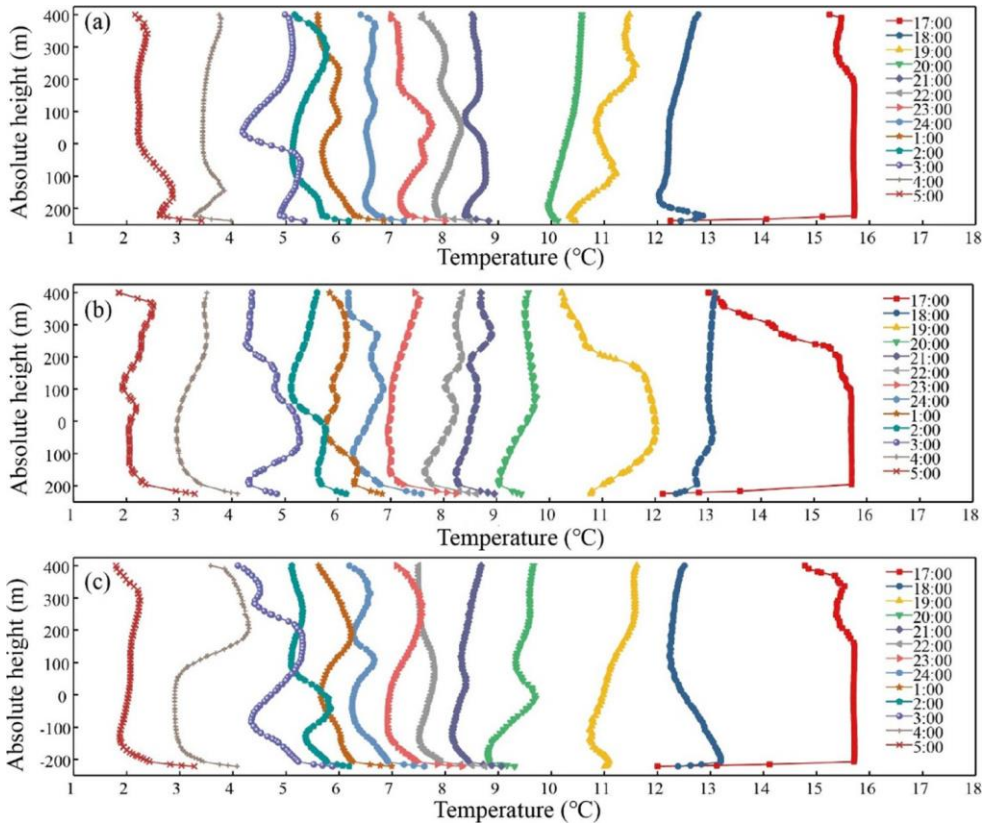
Bingham Canyon Mine (Utah)
1,250 meters depth

Dynamic Mine?
Mine depth changes over mine lifetime
Bingham Canyon: 0 → 1,250 m from 1906 → 2022 = $\langle 10\ \mathrm{m/yr} \rangle$

High elevation?
Air pressure reduced at high elevation.
FC power density reduced due to reduced O2 partial pressure
Radiator fan forced air mass flow rate reduced due to reduced air density

See: Chile https://www.trade.gov/country-commercial-guides/chile-mining
https://earthobservatory.nasa.gov/images/43394/escondida-copper-mine-atacama-desert-chile

Mine near Tangshan 唐山市, China
+80 m → -210 m mine depth



https://pubs.acs.org/doi/pdf/10.1021/acsomega.1c00674

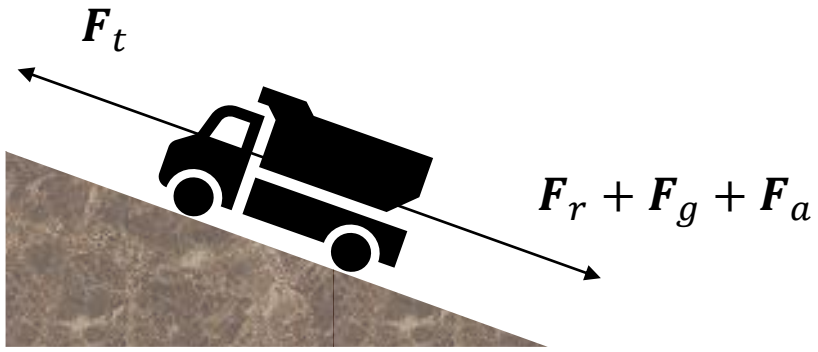
1. USP&E Global listings
2. Power Enterprises listings
3. Power Systems Today listings
4. EPRI Solutions Market Assessment Report

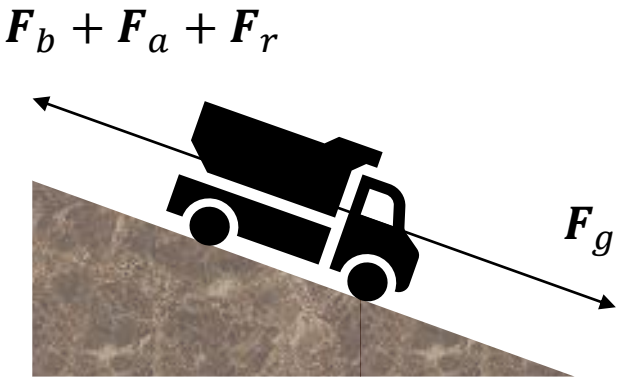
Methodology: Power Demand

Force Balance for Power Demand Duty Cycle

- 1D Vehicle Dynamics Method [1,2,3]
- Forces:
  - $\boldsymbol{F}_t$ = traction force
  - $\boldsymbol{F}_b$ = braking force
  - $\boldsymbol{F}_g$ = grade force
  - $\boldsymbol{F}_r$ = rolling force
  - $\boldsymbol{F}_a$ = aerodynamic drag force

$$m\frac{d}{dt}(\boldsymbol{v}(t)) = \sum_j \boldsymbol{F}_j$$





- Traction and Braking are never simultaneously applied
- 2% rolling resist. factor [3]
  "A hard, smooth, stabilized surfaced roadway without penetration under load, watered, maintained"
- **Model inputs** are haul route, vehicle gross power, vehicle mass

1. Guzella and Sciarretta 2013
2. Terblanche, Kearney, Nehring, and Knights, *Mining Technology*, **128** (2019)
3. Caterpillar Performance Handbook (2015)